OVERVIEW OF SUPERCRITICAL CO_2 POWER CYCLE DEVELOPMENT AT SANDIA NATIONAL LABORATORIES

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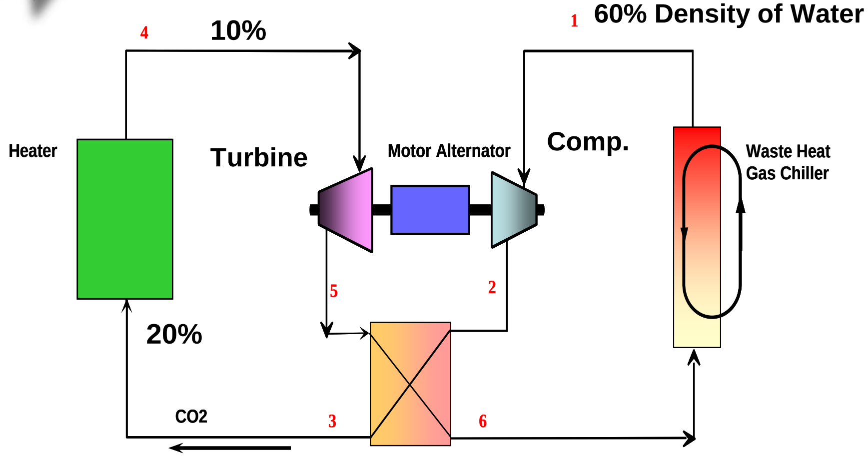
Goals of Presentation

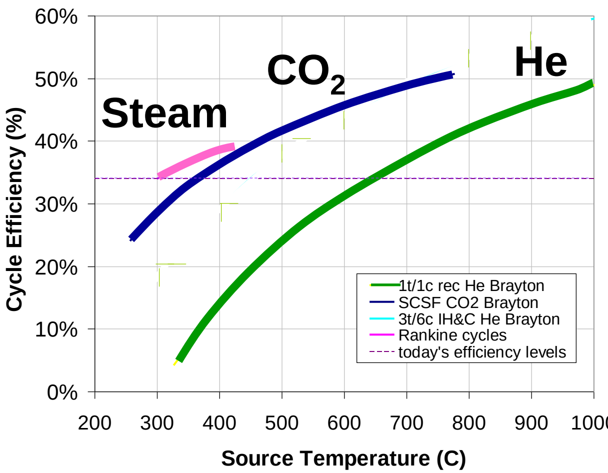
- ***What is a Supercritical CO_2 Brayton Cycle?***
- **Benefits of S-CO_2 Power Systems**
  - **Economic and Environmental**
  - **All Heat Sources**
- **DOE-NE Gen-IV S-CO_2 Research Program**
- **Applications List (Fossil, Solar, Nuclear)**
- **Scaling Study Results (10 MWe)**
  - **10 MWe Development and Demonstration Program Status of Development Effort**
  - **Commercial and Government**
- **Summary and Conclusions**

What is a Supercritical CO_2 Brayton Cycle? How does it work?

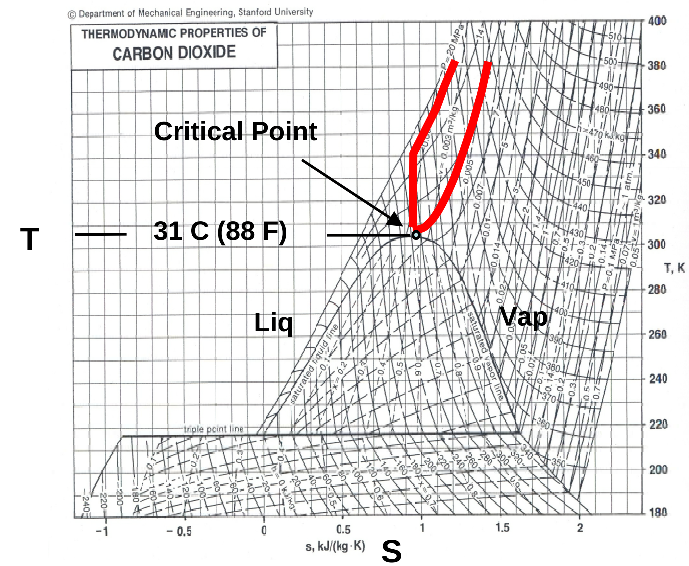


Liquid like Densities with CO_2
Very Small Systems,
High Efficiency due to Low Pumping Power

Cycle Efficiencies vs Source Temperature
for fixed component efficiency

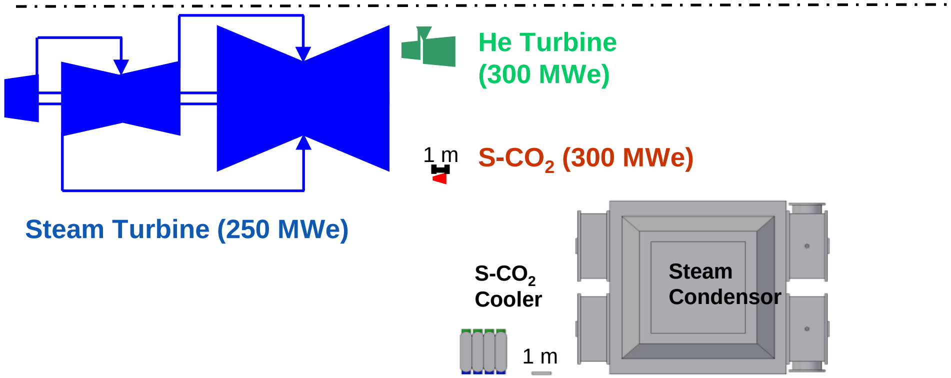


High Efficiency at Lower Temp
(Due to Non-Ideal Gas Props)



Rejects Heat
Above Critical Point
High Efficiency ***Non-Ideal Gas***
Sufficiently High for Dry Cooling

Critical Point
88 F / 31 C
1070 psia / 7.3 MPa



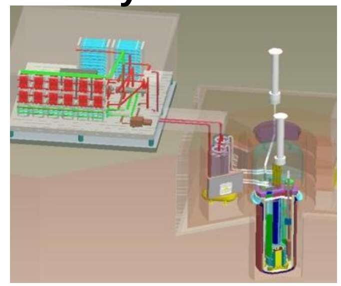
High Density Means Very Small Power Conversion System
Non-Ideal Gas Means Higher Efficiency at Moderate Temperature

Supercritical CO_2 Cycle Applicable to Most Thermal Heat Sources

Solar

SNL Solar Tower

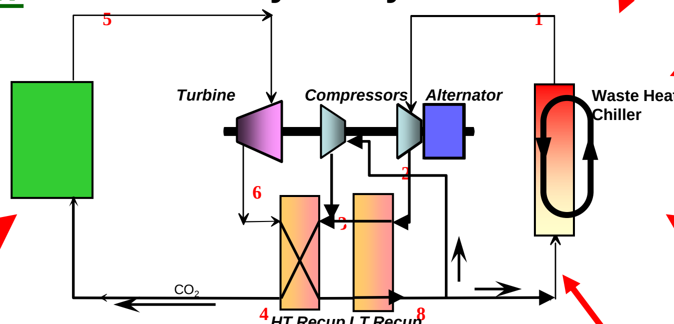
Military **Fix Base & Marine**



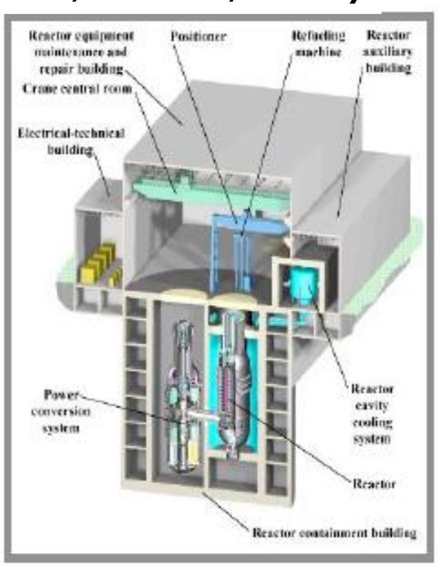
ARRA Geothermal

Waste Heat
Bottoming Cycle to a Gas Turbine

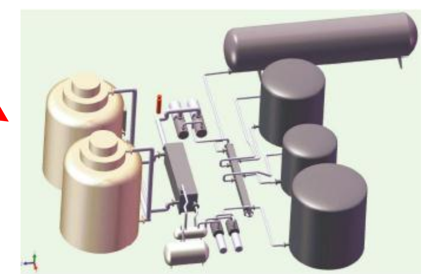
Supercritical CO_2 Brayton Cycle



Nuclear (Gas, Sodium, Water)



DOE-NE Gen IV



Carbon Capture & Sequestration
CCS+EOR
Fossil Oxy-Combustion

Energy Storage & Heat Transport & CCHE

SNL has Funding or Research Agreements with most Agencies Representing these Heat Sources

Key Features to a Supercritical Brayton Cycle

- Peak Turbine Inlet Temp is well matched to a Variety of Heat Sources (Nuclear, Solar, Gas, Coal, Syn-Gas, Geo)
- Efficient ~43% - 50% for 10 - 300 MW_e Systems
  - 1000 F (810 K) ~ 538 C Efficiency = 43 %
  - 1292 F (1565 K) ~ 700 C Efficiency =50%
- Advanced Systems (Increase Eff 5-8% points) & Dry
- Standard Materials (Stainless Steels and Inconels)
- High Power Density for Conversion System
  - ~30 X smaller than Steam or 6 X for Helium or Air
  - Transportability (Unique or Enabling Capability)
  - HX's Use Advanced Printed Circuit Board Heat Exchanger (PCHE) Technology
- Modular Capability at ~10-20 MWe
  - Factory Manufacturable (10 MW ~ 2.5m x 8m)

Gen IV S-CO2 Brayton Cycle

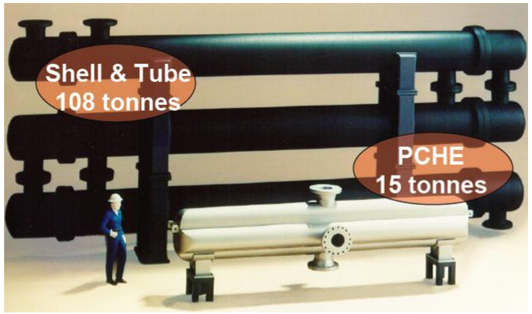
Turbine Building

Steam

$S\text{-}CO_2$

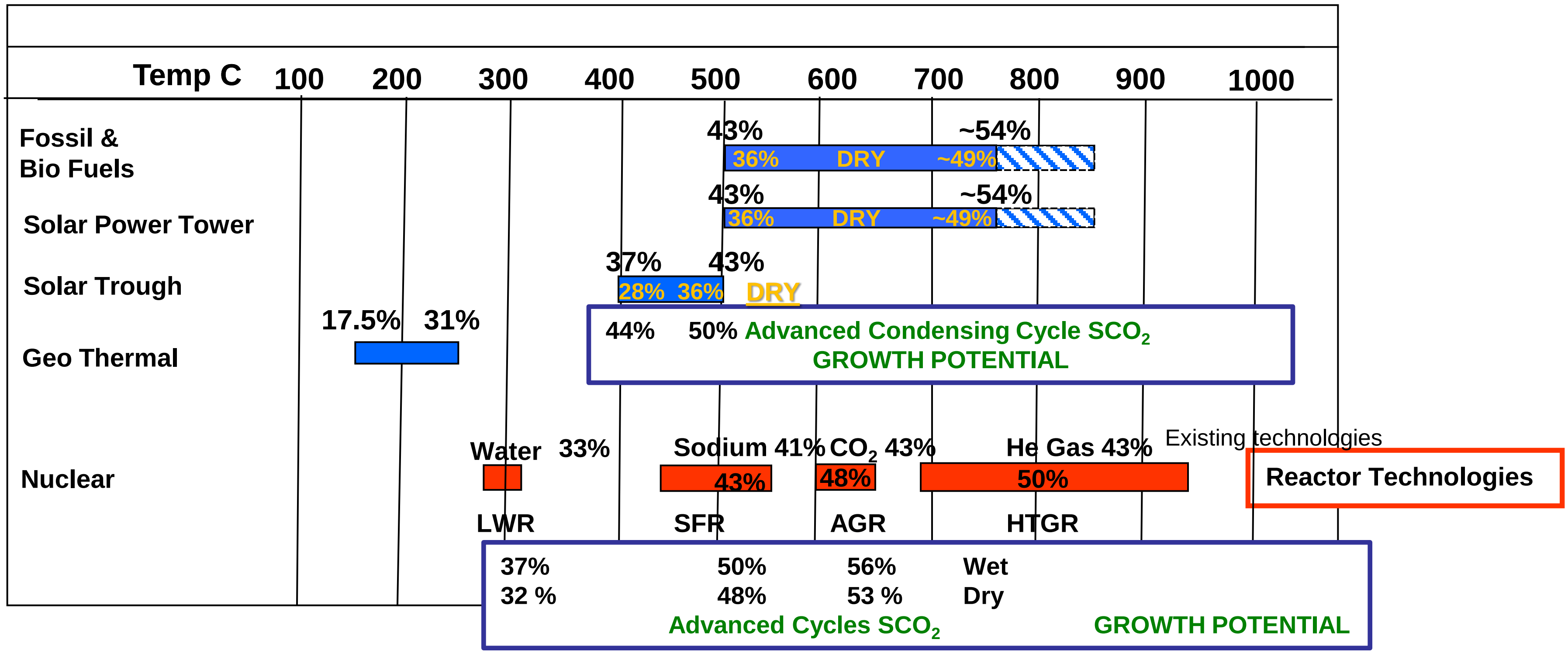
Good Efficiency at Low Operating Temps
Standard Materials, Small Size, Simple,
Modular & Transportable
AFFORDABLE and FABRICABLE

Modular & Self Contained Power Conversion Systems ~ 1.5 m x 8 m



Advanced Heat Exchangers Meggit / Heatric Co.

Heat Source Operating Temperature Range & SCO_2 Power Conversion Efficiency for Various Heat Sources



S-CO_2 Power Conversion Operating Temperatures are Applicable for All Heat Sources
Optimum Design Requires Different Approaches for Each Heat Source
Supercritical Fluid Technology has Untapped Growth Potential

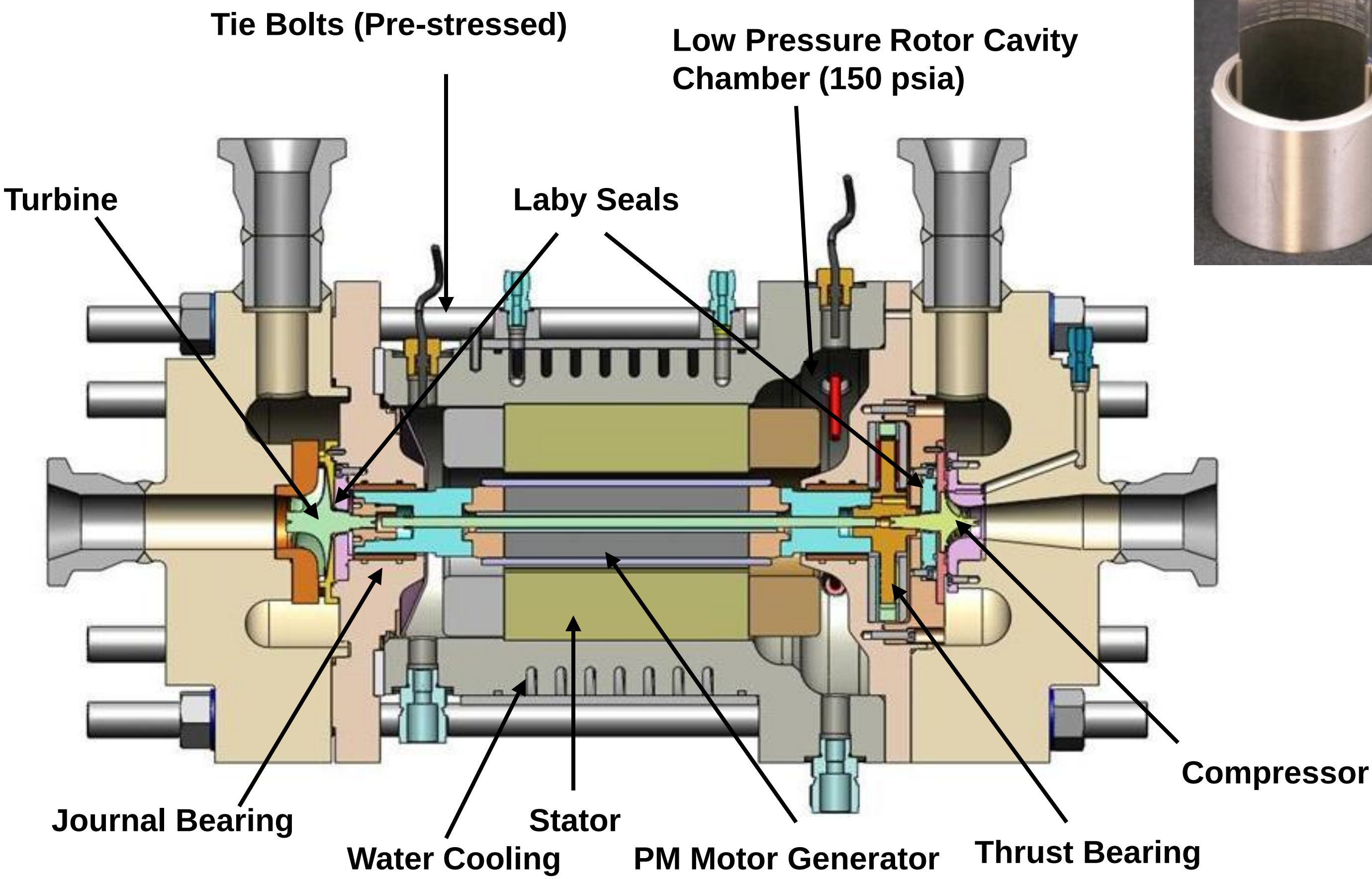
Assumptions (Turbomachinery Eff (85%/87%/90% : MC/RC/T), 5 K Approach T, 5% dp/p losses, Hotel Losses Not In Included, Dry Cooling at 120 F)

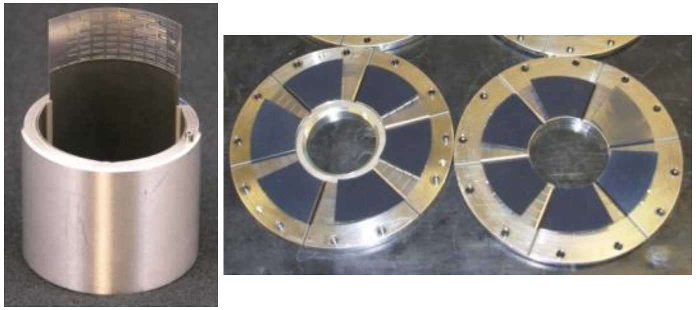
DOE Supercritical CO_2 Program Description

- **DOE Gen-IV S-CO_2 Research Program**
  - **Sandia has developed two S-CO_2 loops**
    - Compression Loop (At Sandia) + Brayton Loop (At Barber-Nichols)
    - Testing Summary
      - **Brayton and Compression Loop Descriptions**
      - Compressor Performance Mapping
      - **Power Generation in Simple Heated Brayton Cycle and in Split-Flow Re-compression Brayton Loop**
      - Mixtures
      - Condensation Cycles / Rankine
      - Gas Foil Bearing Development
      - Thrust Bearing Heating
      - High Speed PM Motor Generator Controller Development
      - Sealing Technology
    - Modeling
    - Ability of Sandia S-CO_2 Brayton Loop to Reproduce Other Cycles
    - **Summary and Conclusions**

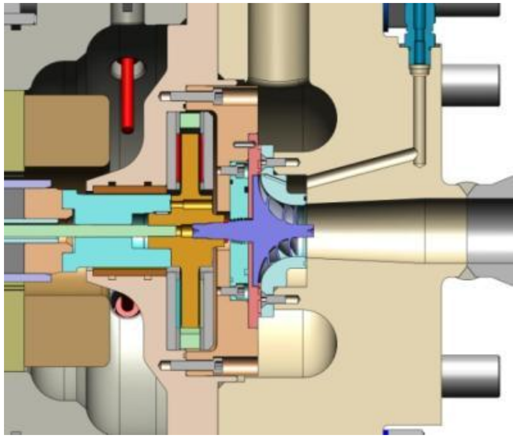
Key Technology

Turbo- Alternator Compressor Design
Permanent Magnet Generator with Gas Foil Bearings
~24” Long by 12” diameter





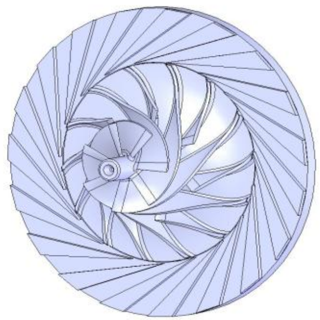
Gas-Foil Bearings



125 kWe at 75,000 rpm

Turbomachinery Wheels

Designed and Manufactured By Barber-Nichols Inc.



Main Compressor

Re-Compressor

Turbine for Re-Compressor

Turbine for Main Compressor

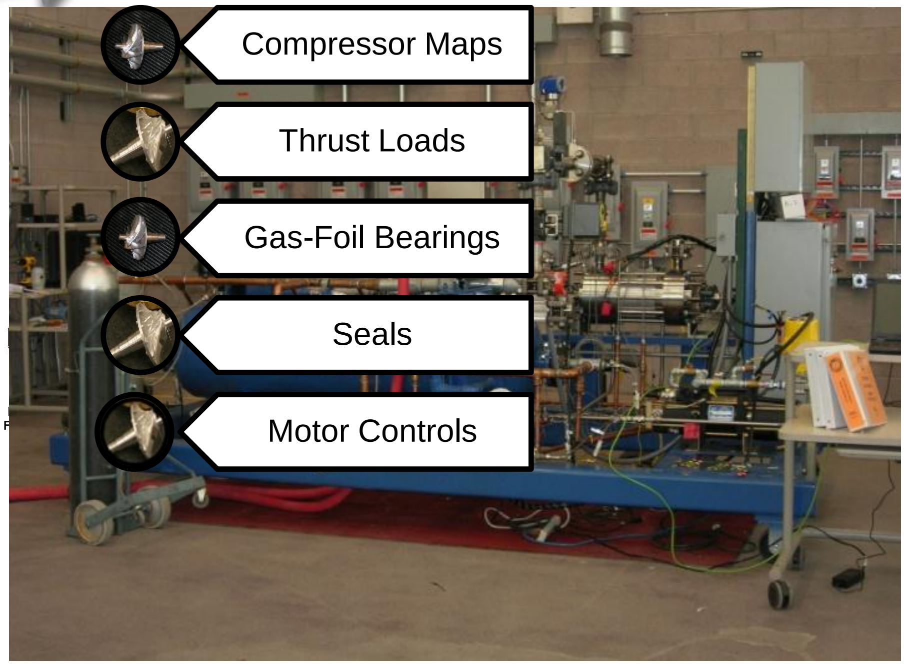
OD=37.3 mm
1.47”

OD=57.9 mm
2.27”

OD=68.3 mm
2.69”

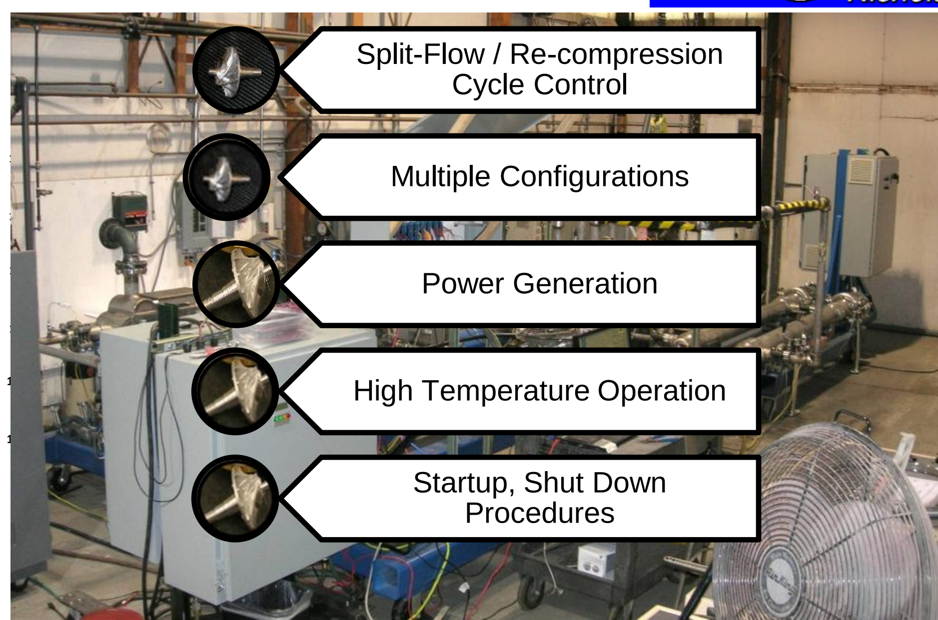
OD=68.1 mm
2.68”

$S\text{-}CO_2$ Development Sequence



Sandia Single Compressor Loop

Barber Nichols

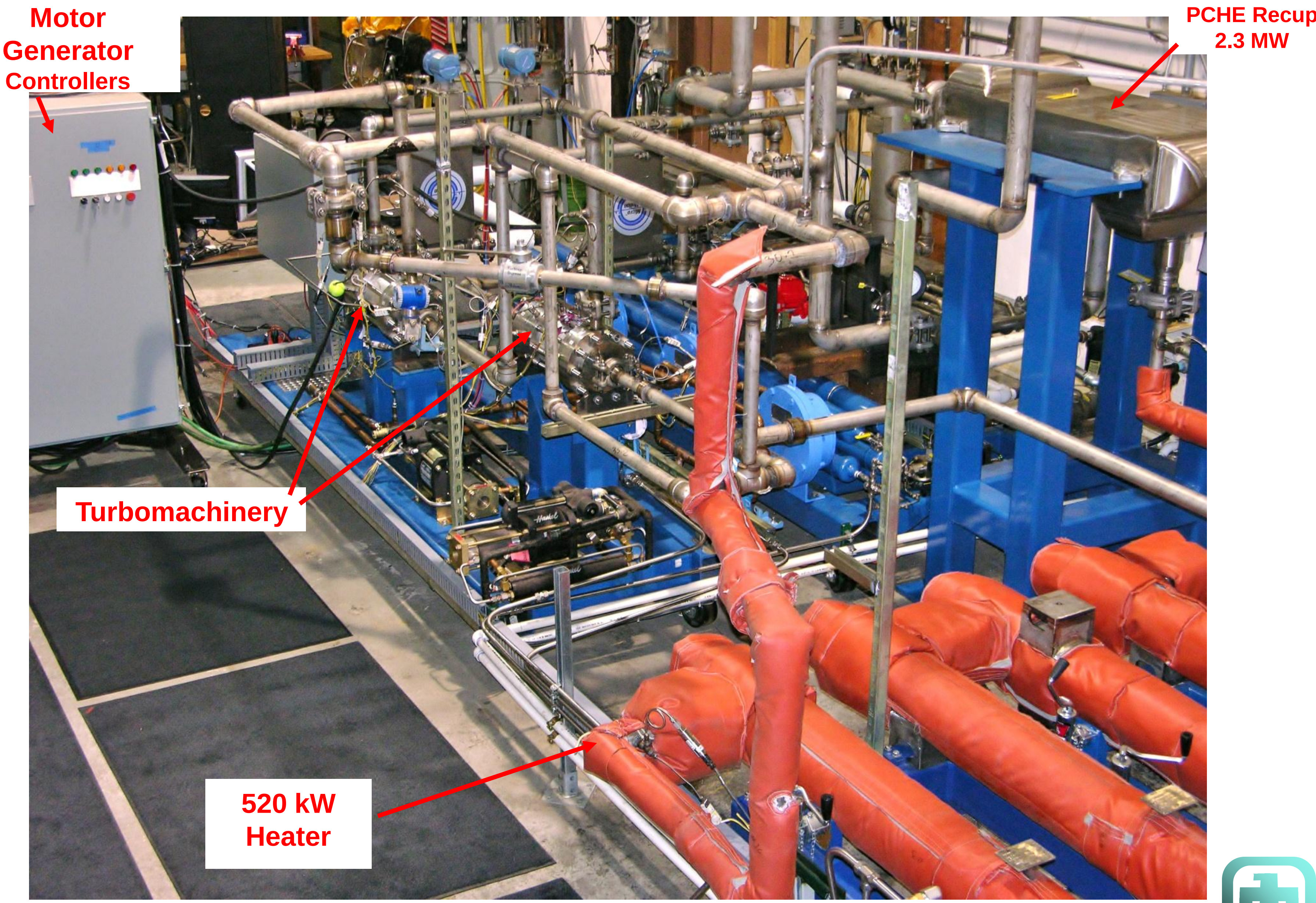


Other Supercritical Fluids (SF_6)

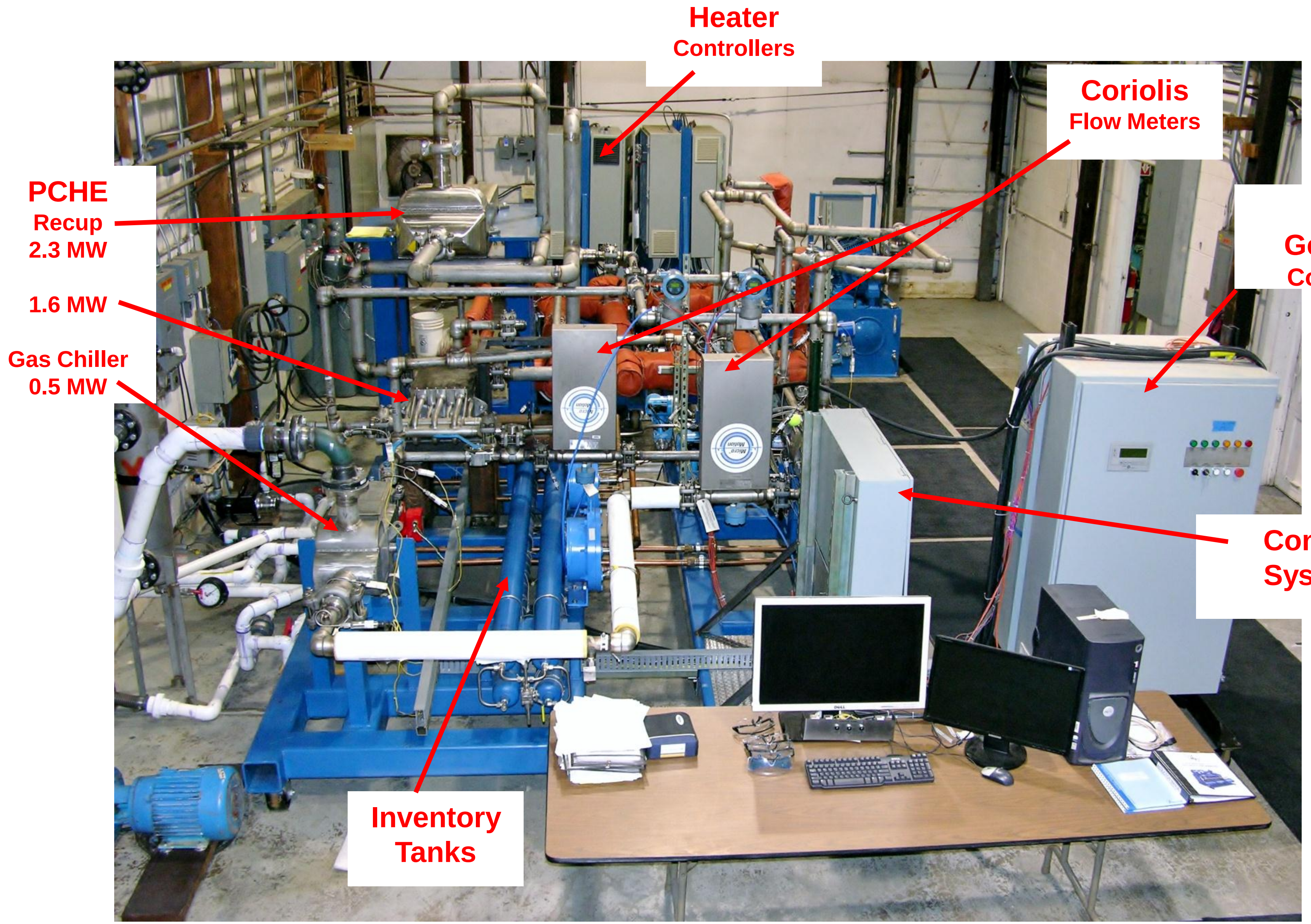
Supercritical Mixtures

Condensation Cycle

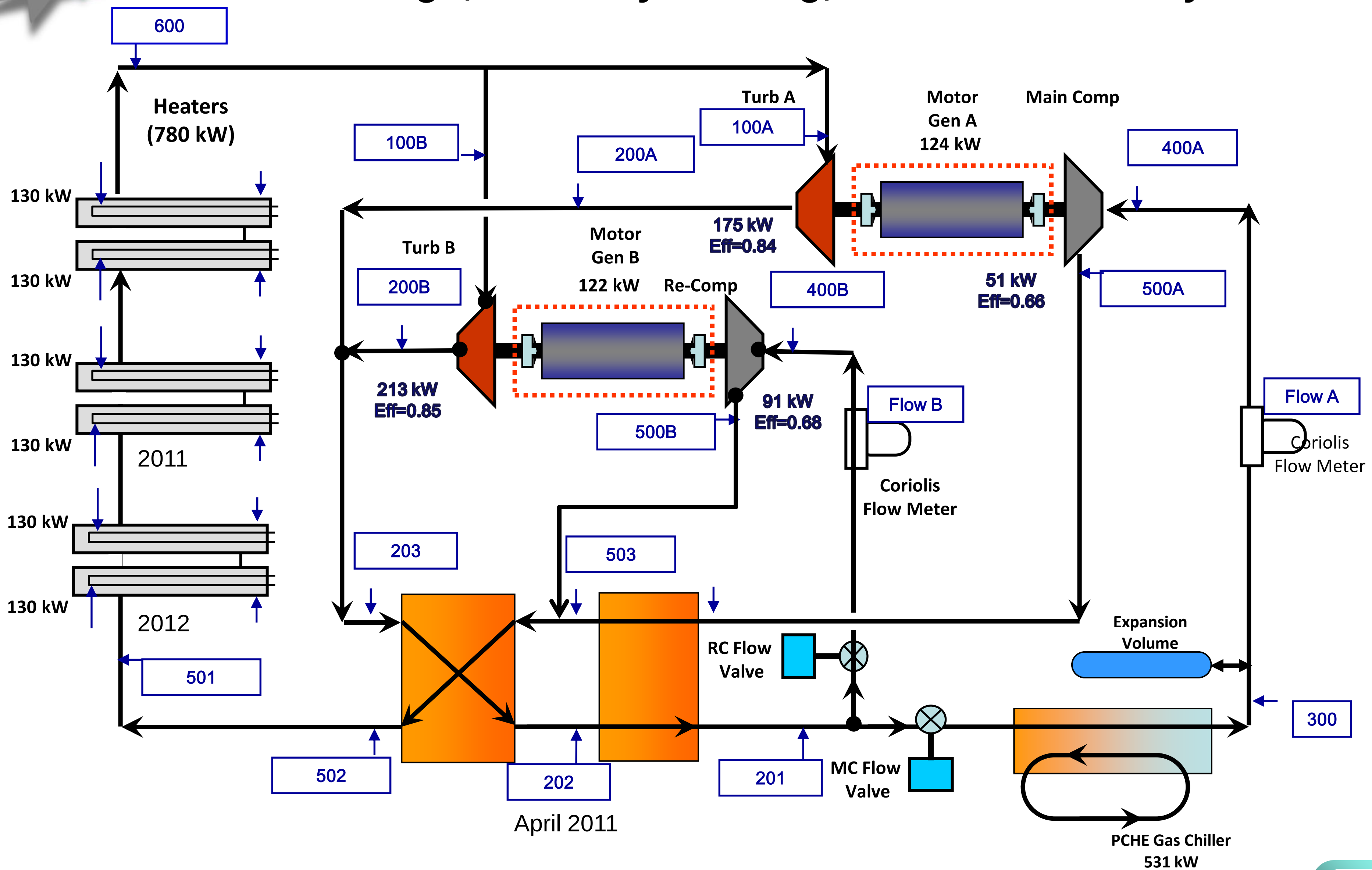
GenIV-Supercritcal CO_2 Brayton Cycle Loop



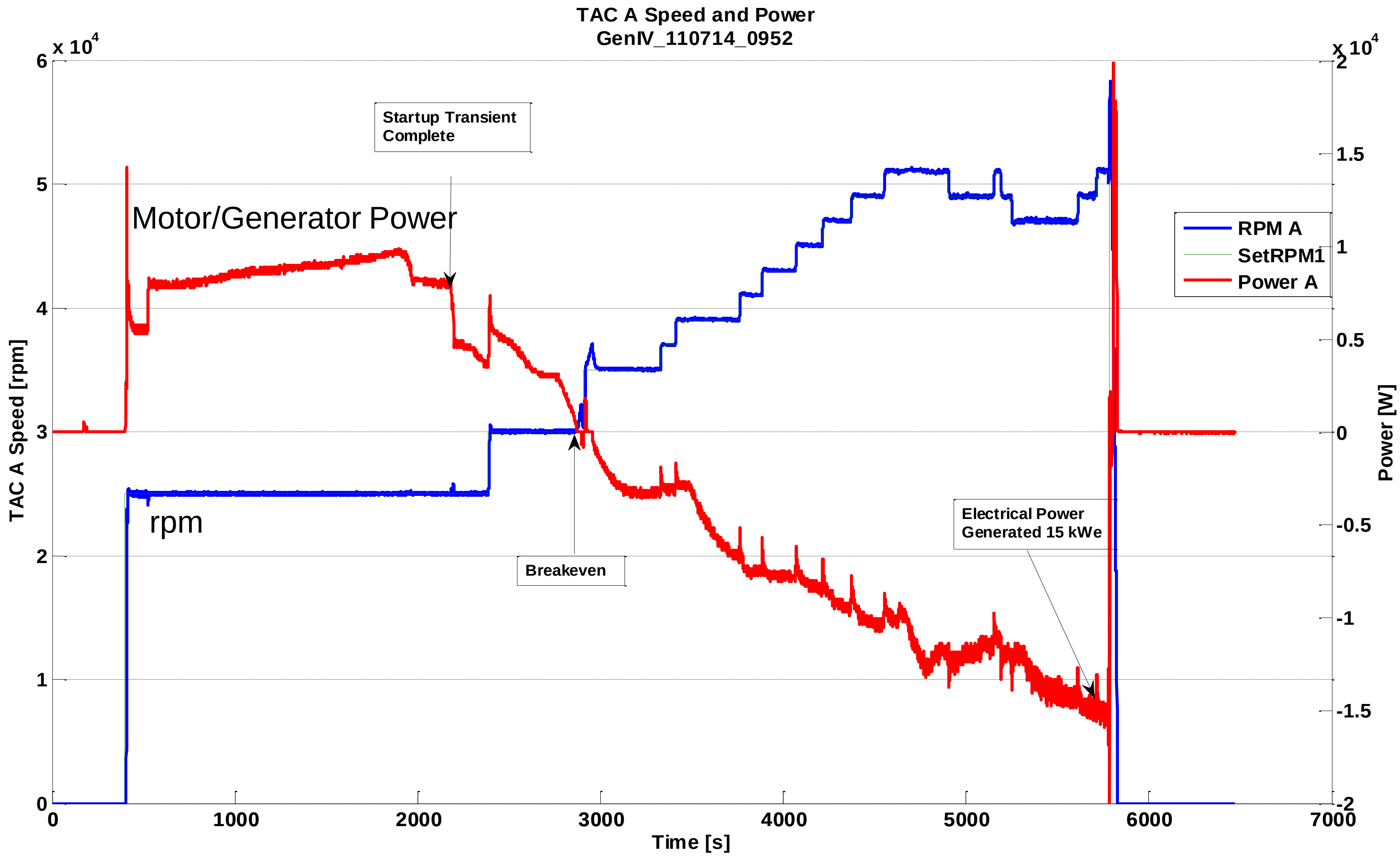
Supercritical S-CO_2 Brayton Cycle DOE-Gen IV



Supercritical CO_2 Brayton Loop
Final Design, Currently Existing, and Alternative Layouts

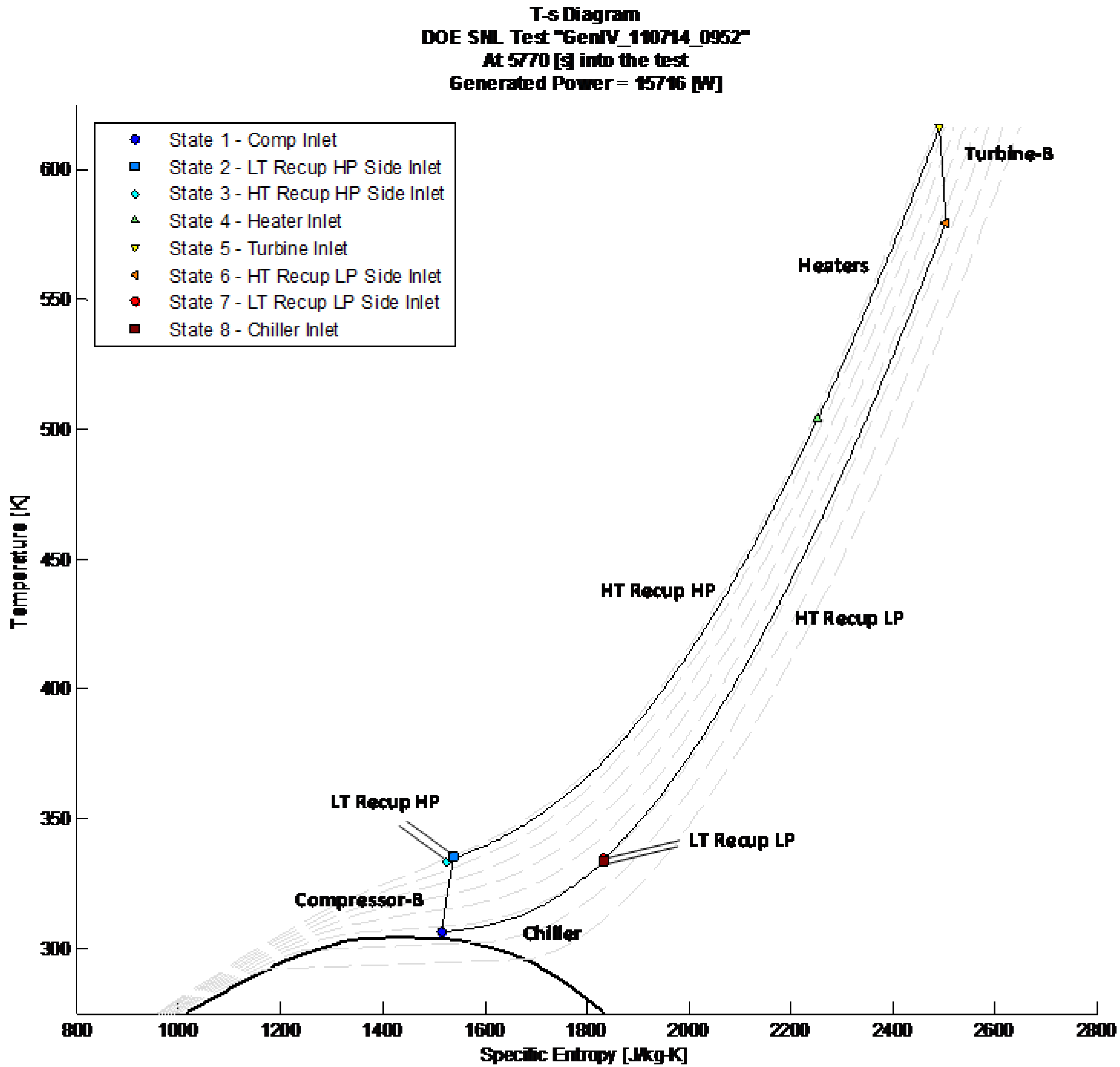


Power Generation in Upgraded S-CO2 Simple Heated Recuperated Brayton Loop



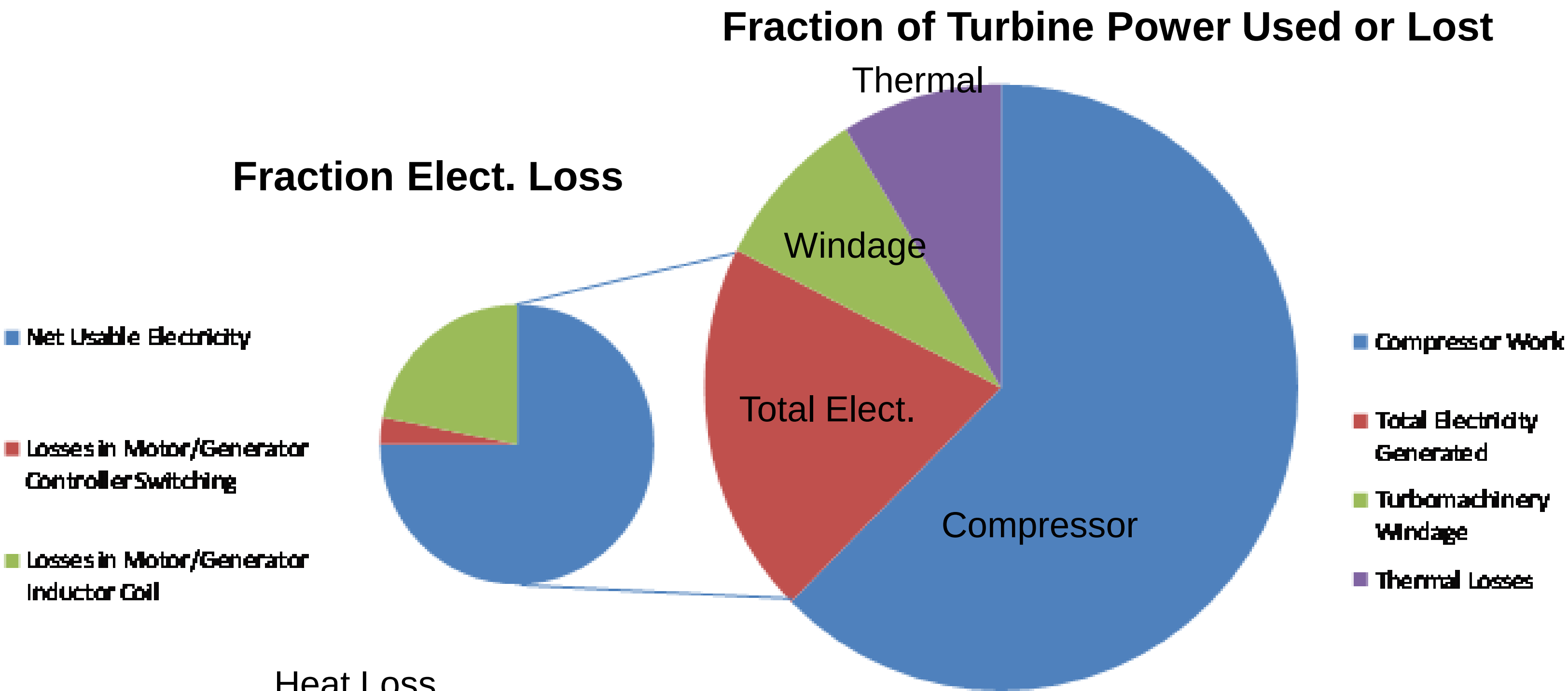
Measured T-S Diagram

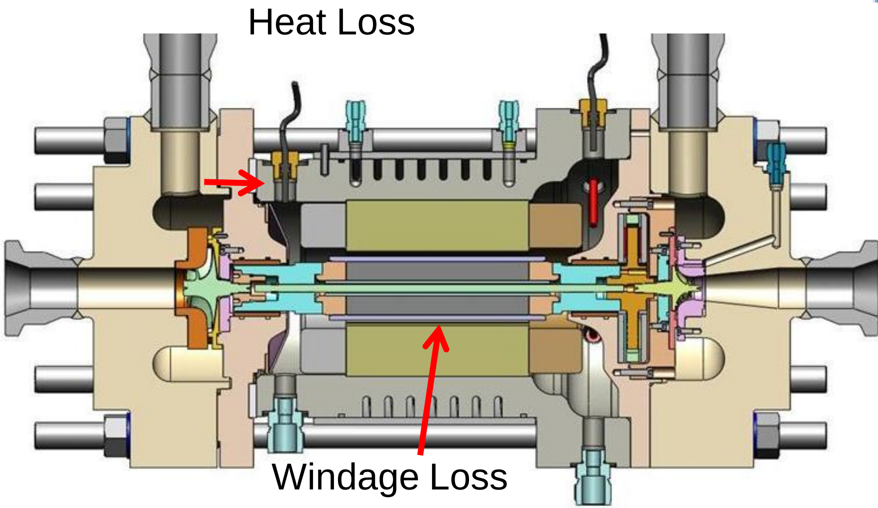
GenIV_110714_0952



Loss Measurements

C-2 Compressor T-2 Turbine



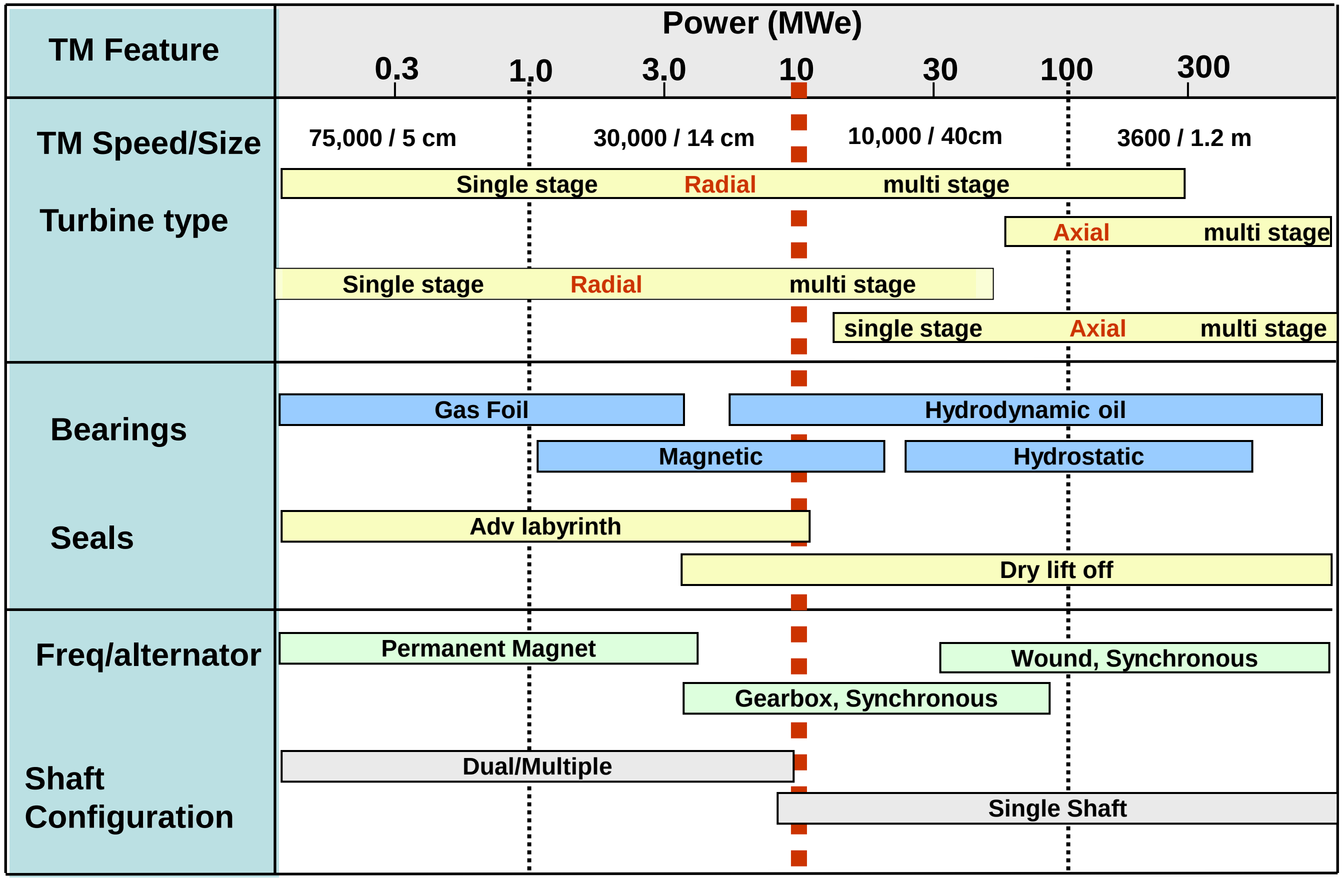


$S\text{-}CO_2$ Power Cycle Economic and Environmental Benefits

- DOE has invested 5 years and ~ $10-11 M on Proof-of-Principle $S\text{-}CO_2$ Power Systems
- The Potential Economic and Environmental Benefits of $S\text{-}CO_2$ Power Systems are Large
  - Useful with All Heat Sources
  - Dry Cooling, Oxy-Combustion with CCS and EOR, Smaller, Simpler, Improved Efficiency
- Development is Still Needed
  - To date only small scale proof-of-concept development loops are operating
  - Heat Source and Power Cycle are Linked (Cycle/Design Research)
  - Heat Exchanger Development is Needed
    - Micro-Channel Design Costs, Transient Cycling, Packaging, Failure Modes, Cost Reductions, Nuclear Certification
  - Commercial Engineering and Demonstration is Needed using Industrial Hardware (~10 MW_e)
    - Already started in industry
    - Government/Industry Partnership Role Makes Sense

Scaling Study

Scaling Rules and Ranges of Application for Key Brayton Cycle Turbomachinery Components



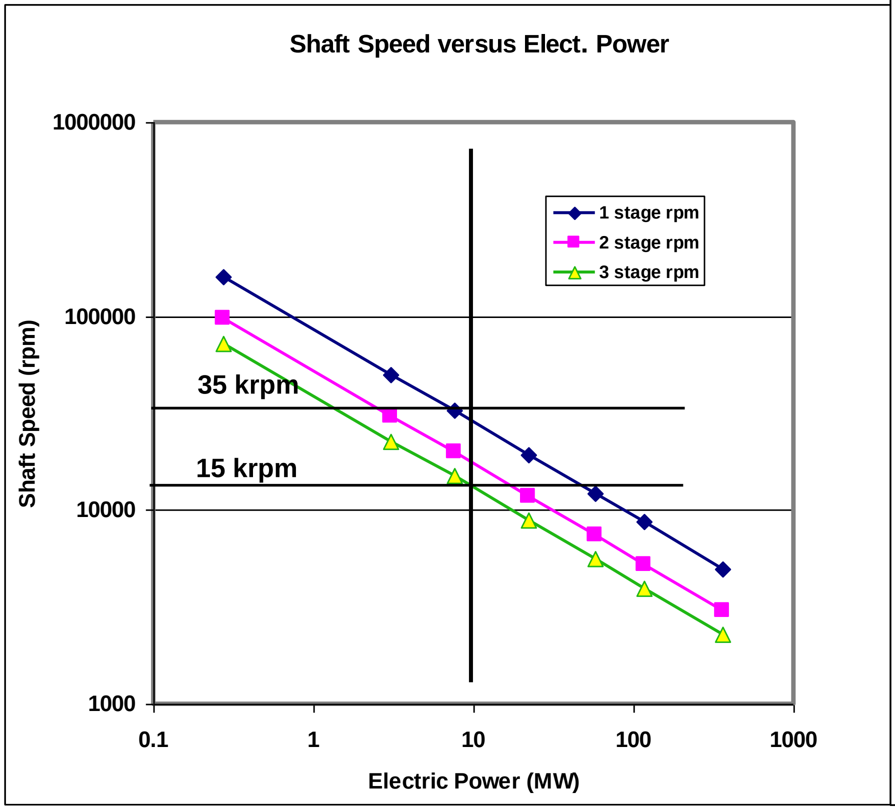
High Technology
High $/kWe

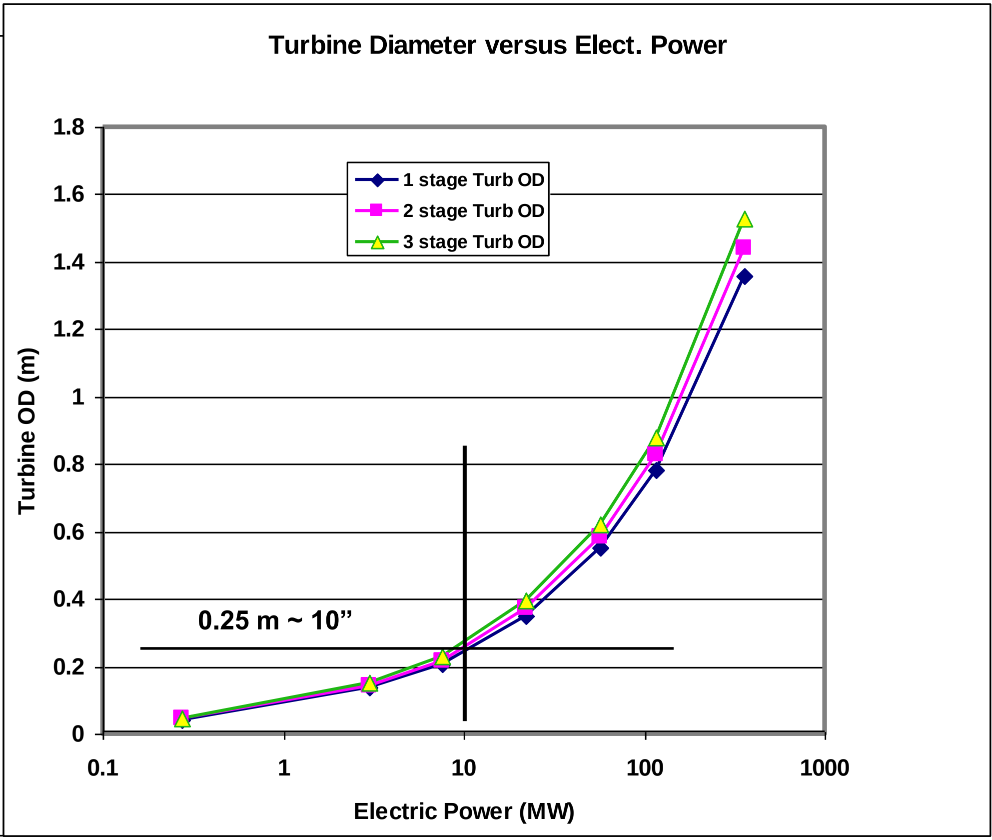
→

Commercial Technology
Lower $/kWe

- **10 MWe allows use of Commercial Technologies**

Approximate Shaft Speed and Turbine Wheel Diameter

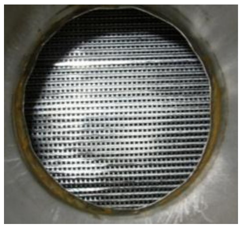




Printed Circuit Heat Exchanger Scaling Rules

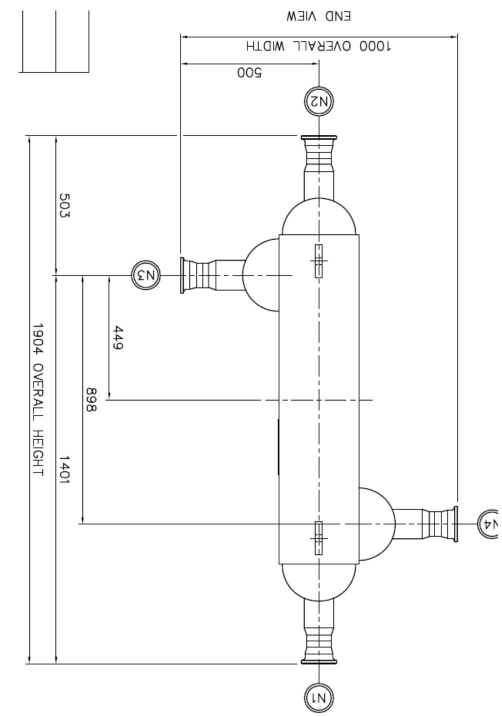
	Actual			Specific Costs	
Cost	**kW**	**lb**	**lb/kW**	**$/lb**	**$/kW$_{th}$**
60000	510	492	0.96	122	118
106000	1600	551	0.34	192	66
210000	2300	1410	0.61	149	91
Average			0.64	154	92

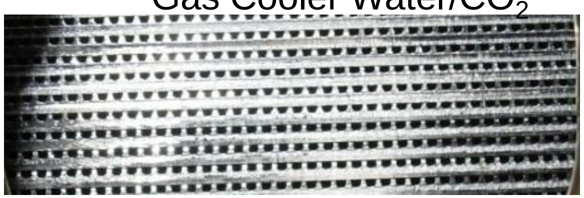
= $ 600/kW$_e$



Gas Cooler Water/CO_2

LT Recup





Need Cost Reductions (Materials, Scale, & Advanced Manuf.) to reach 200$/ kWe

Potential Applications

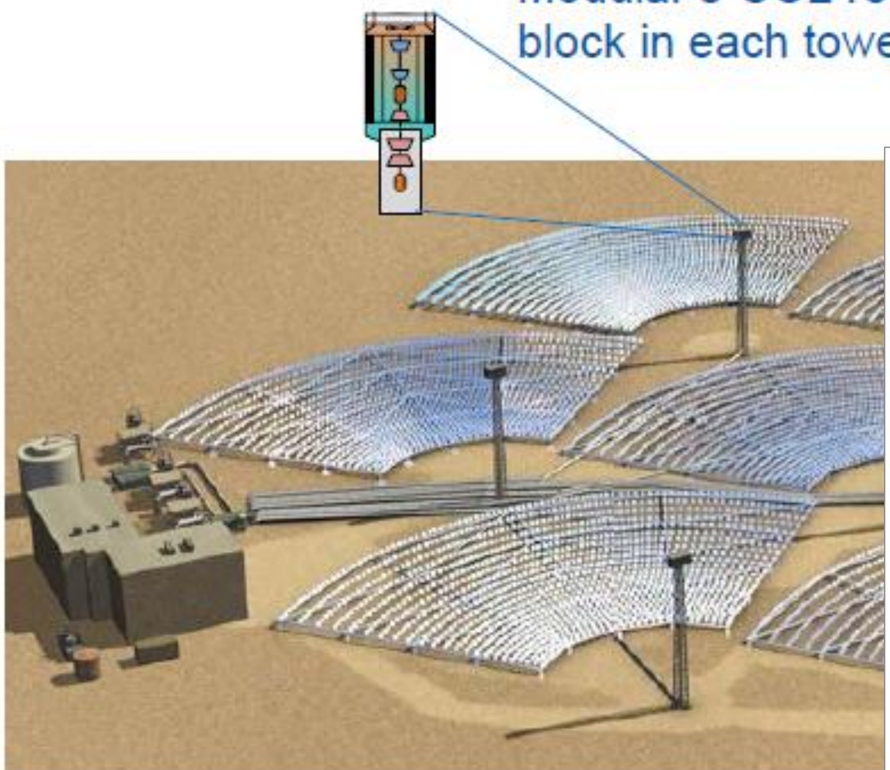
- Nuclear
  - (LWR, SFR, GCR, Molten Salt Reactors)
- Concentrated Solar Power (CSP) Towers + Troughs
- Military (Fixed Base and Marine)
- Fossil
  - Oxy-combustion with Pulverized Coal with CCS + EOR
- Solar Power Towers
- Integrated Bio-Fuel/SCO_2 Plant
- Military Applications (Fixed Base and Marine)
- Geo-Thermal
- Waste Heat Applications
  - Gas Turbine Bottoming Cycle
  - Supercritical Water Oxidation

Concentrated Solar Applications

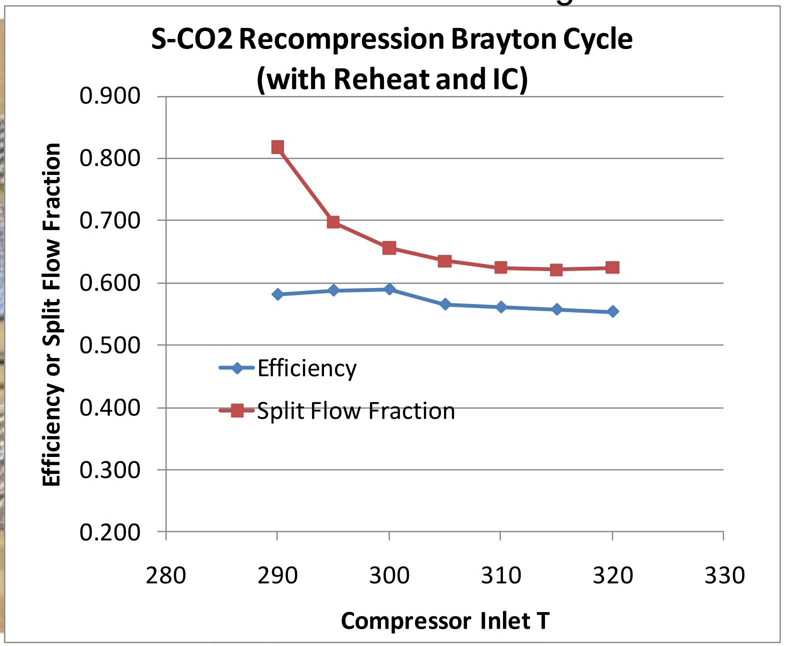
Small or Big ?

1-10 MWe or 100 MWe

Modular s-CO2 receiver / power block in each tower…

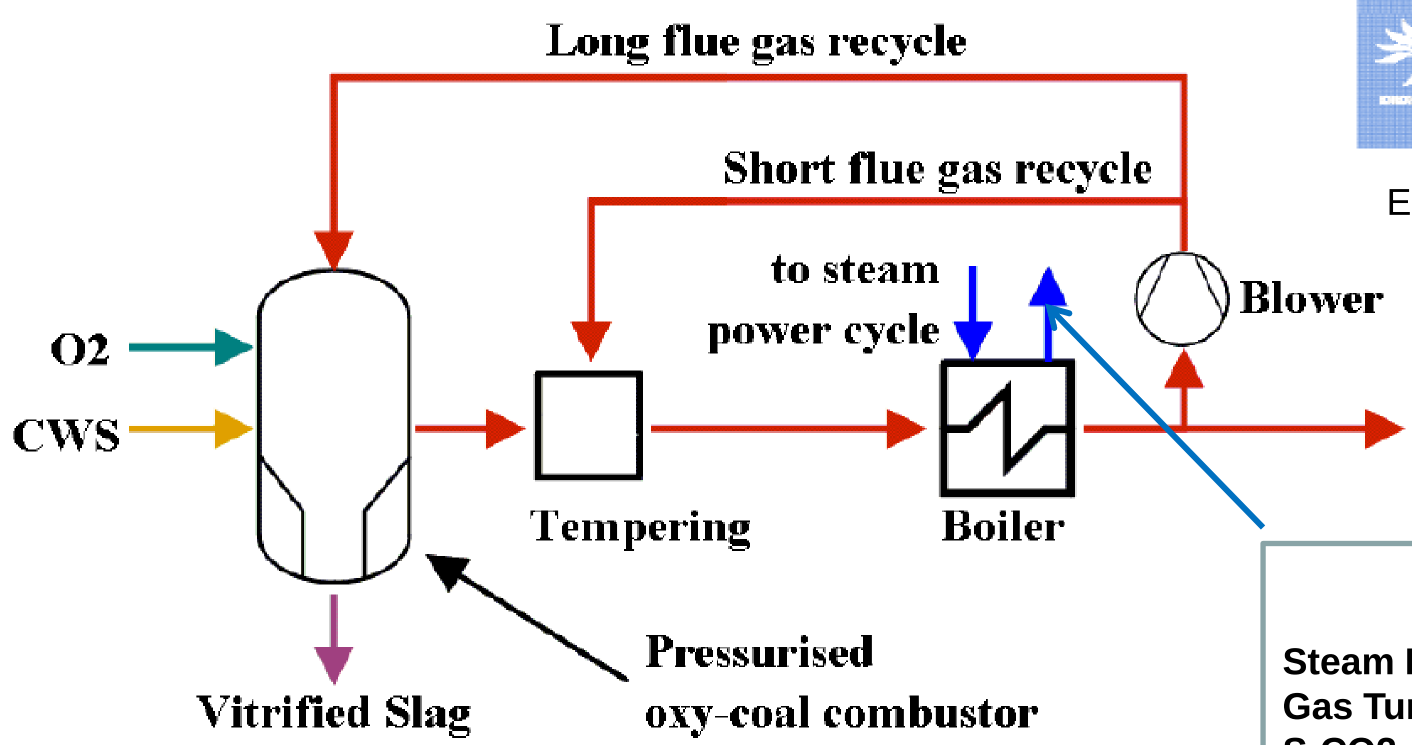


Advanced S-CO_2 Power System
Reheat and Inter-Cooling   TIT=700C



or centralized s-CO2 power block with salt receivers?

Fossil Application
Oxy-Coal Combustion



ENEL (Italy)

Steam Rankine (ENEL)
Gas Turbine (CES)
S-CO2
Or Combinations (PWR)

Nuclear Applications

Why is DOE-NE Interested?

1) Better efficiency than existing plants

2) Smaller Power Plants

(30% of Steam)

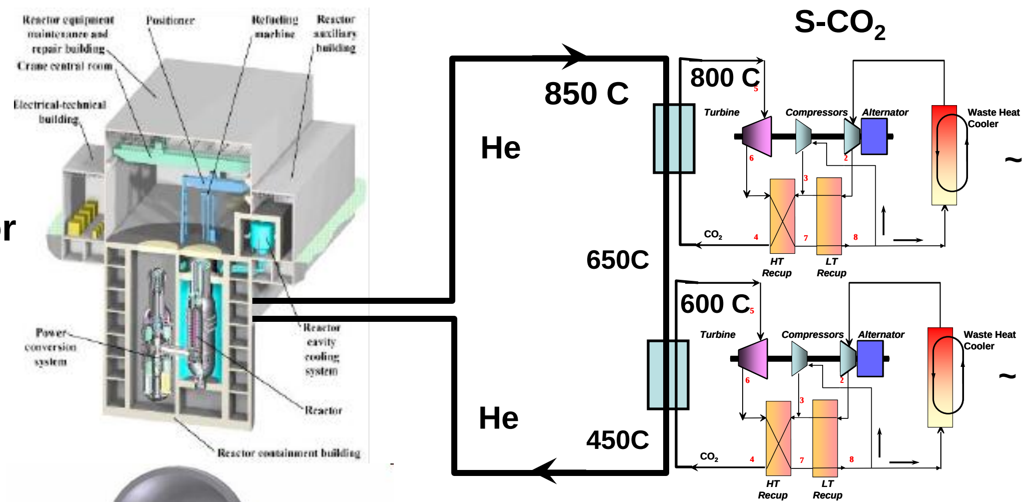
3) Simpler Power Plants

($1/10^{th}$ number of valves)

4) May Eliminate the Intermediate Loop in Sodium Fast Reactors

S-CO_2 Power Cycles for Reactors

NGNP
High Temperature
Gas Cooled Reactor
850-900 C



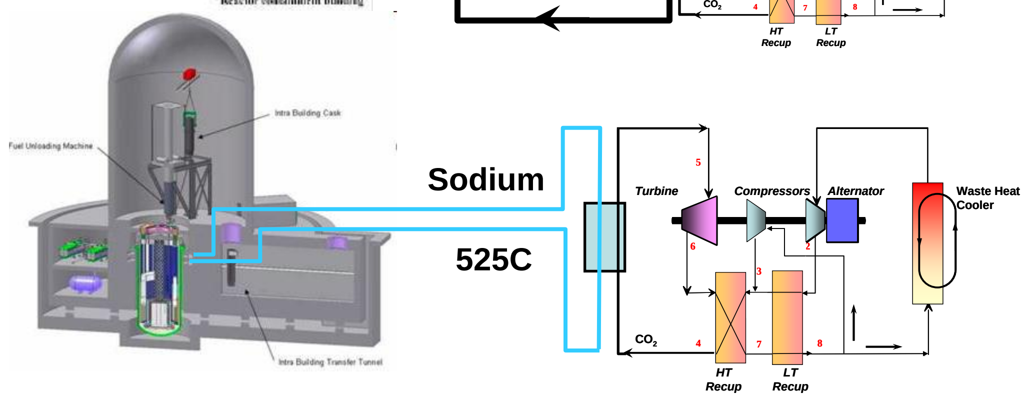
GCRs

~ 54 %

~ 50 % Efficiency
(S-CO_2 Brayton)

~ 46 %

Sodium Cooled
Reactor
500-550 C

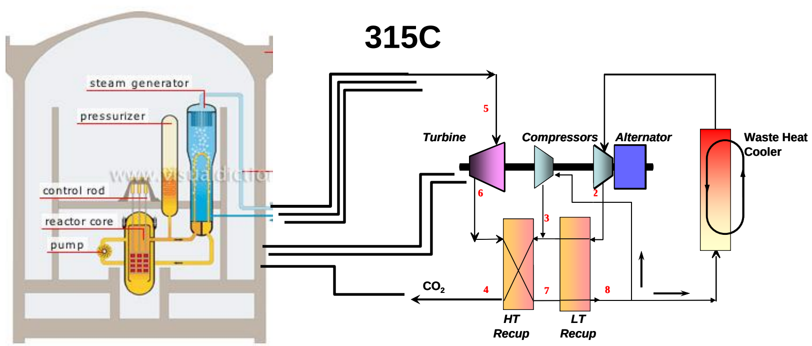


SFRs

~ 43 % Efficiency
(S-CO_2 Brayton)

LWRs
Pressurized
Water Reactor
330 C

Potential SMR
Applications



LWRs

~ 40 % Efficiency
(S-CO_2 Recup Rankine
Condensing Brayton)

Sandia Research Program Summary

- **Sandia/DOE have two operating S-CO_2 test loops**
  - Research Compression Loop
  - Reconfigurable Brayton Loop
- **Measured Main Compressor Flow Maps**
  - Overall Good Agreement with Mean-Line Predictions of the Performance Maps
  - Over a wide range of operating Temperature, pressure, and density
- **Using Brayton loop Configuration available in FY2010 and 2011**
    - Heater power was limited to 260/390/520 kW
    - Produced Power in simple heated recuperated Brayton loops (Main TAC and Re-Comp TAC)
    - Power Production in recompression loops (still limit to break even)
    - Cold Startup, Breakeven, Power Production (6% efficiency and 20 kWe), Power/RPM Operation Maps
- **Condensation in Tube and Shell and PCHE heat exchangers**
  - Improved Efficiency, HX Development work is beginning
- **Test (critical point) were performed with Mixtures of CO_2, CO_2-Neon, CO_2 SF_6, CO_2-Butane**
  - Can Increase or decrease T_{crit}
  - Improved Efficiency (especially for low temperature applications)
- **Thrust Gas Foil Bearing Tests and Modeling**
  - Goal : higher thrust load capability and lower frictional power
- **Natural Circulation**
  - S-CO_2 Gas Fast Reactor
  - C3D CFD Model development
- **Collaborations with Industry + Larger Scale System Development**

Path Forward

- **Path Forward**
  - **Continue Testing of Proof-of-Principle Small Loop**
  - **Work/Collaborate with Industry and other Agencies to develop $S\text{-}CO_2$ System for any heat source at the 10 MW_e sized system**
  - **Propose for First Nuclear Applications**
    - **Use with LWRs**
    - **Wet and Dry Cooling**
    - **37% and 30% Efficiencies**
    - **Develop S-CO2 Systems for Nuclear Technology**
- **Begin Seeking Gov. Funded 10 MWe S-CO2 power system development to support FE, EERE, NE, Other**
  - **Useful for all heat sources (Nuclear, Solar, Fossil, Geothermal)**
  - **Numerous early non-nuclear Products (Marine, Fossil, Solar, Geo, Waste Heat, Heat Storage and Transport)**
  - **Improved the economic and environmental benefits for all systems (Smaller, Simpler, more Efficient, No Water Cooling)**

S-CO_2: Potential

Potential for S-CO_2 Power Generation Systems to Improve Economics and Environmental Issues on a Large Scale

1) *Dry Cooling*
2) *Oxy-Combustion, with CCS and EOR*
3) *Smaller and Simpler (than steam)*
4) *Improved Efficiency*
5) *Combined Heating, Cooling, and Power Cycles*

Applicable For All Types of Heat Sources